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Citation: Journal of Applied Physics **95**, 6696 (2004); doi: 10.1063/1.1690971
View online: http://dx.doi.org/10.1063/1.1690971
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/95/11?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS VOLUME 95, NUMBER 11 1 JUNE 2004

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(Presented on 6 January 2004)

A superconducting Nb thin film with triangular arrays of pinning sites has been fabricated to investigate the commensurate vortex lattices. Vortex-vortex interactions in this pattern film make the observed anisotropy in the pinning properties. Periodic minima appear in the magnetoresistance curves at equal field intervals that can be associated with matching effect. The transport properties at near critical temperatures show anisotropic pinning properties related to the configuration of pinning centers. The critical current is depressed when the driving force is applied along the short diagonal in the rhombic unit cell of pinning array. It implies that the pinning potential along the short diagonal creates a moving channel of vortices in triangular arrays of defects. The pinned and interstitial vortices can be movable in an incommensurate vortex row and a straight unhindered one-dimensional path. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1690971]

I. INTRODUCTION

The flux pinning behavior in type II superconductors is strongly influenced by the presence of defects that act as pinning centers. A rich variety of static and dynamical phases can occur due to the competition between the vortex-vortex and vortex-pin interactions. Nowadays, studying the interaction between the vortex lattice and the arrays of submicrometric pinning centers remains one of the most interesting works.[3–11] Theoretical simulations,[1,2] as well as experiments[3–11] in periodic pinning arrays, including holes, antidots, and magnetic dot arrays, etc., have found numerous commensurability effects in which the pinning is enhanced at applied fields where the number of vortices equals an integer or a rational fraction of number of pinning sites. The flux pinning force and pinning mechanisms corresponding to pinning centers can be understood in terms of investigating the matching effect in an array of defects in transport and magnetization measurements. In previous reports, the pinning force could be affected by the characterization of pinning dots, i.e., Ni, Ag, Co/Pt, etc.[5–7,10,11] but the pinning mechanisms are still worth exploring. In addition, it is not yet fully understood that the pinning centers with size of the order of the relevant length can pin either one vortex or multiquanta vortices. For small pinning sites, only a single vortex will be trapped at an individual pinning center and the interstitial vortices play an important role on the dynamics of flux vortices. The recent development has even provided a method for the analysis of the anisotropic pinning effect with rectangular magnetic dot array[6,7] and triangular blind antidotes.[3,4] Herein, another way is provided to deal with these problems. Two different current paths are applied along the triangular arrays of circle pinning sites to investigate the anisotropic properties of pinning effect. The magnetoresistance (MR) and critical current (I_c) curves reveal strong anisotropic properties that allow us to study the interaction between flux lines and pinning centers.

II. EXPERIMENT

Arrays of submicrometric holes with 70 nm depth have been prepared on SiN-coated Si wafers by using electron beam lithography in conjunction with reactive ion etching. This process is similar to that published in our previous reports.[8,9] The patterned films with four-terminal geometry were completed by a dc sputtering of the niobium film over the triangular hole arrays. Figure 1(a) shows a scanning electron microscope (SEM) micrograph of triangular arrays of corrugated pinning sites with the spacing of 545 nm and the hole diameter of around 300 nm, which are embedded in the 100 nm thick superconducting Nb thin film. These length scales are comparable with the superconducting coherence length of Nb close to critical temperature (T_c). MR measurements were carried out by a four-probe technique in a SQUID system with a low temperature fluctuation within 3 mK, and the external magnetic field was applied perpendicular to the film plane and transport current. Also, the geometry of Fig. 1(a) allows the driving current to be applied along two directions. These two current paths can be applied with respect to the rhombic unit cells of the triangular arrays of pinning sites, as sketched in Fig. 1(b). Case A is for the current along the short diagonal and case B is for the current along the long diagonal direction. The resistance measure-

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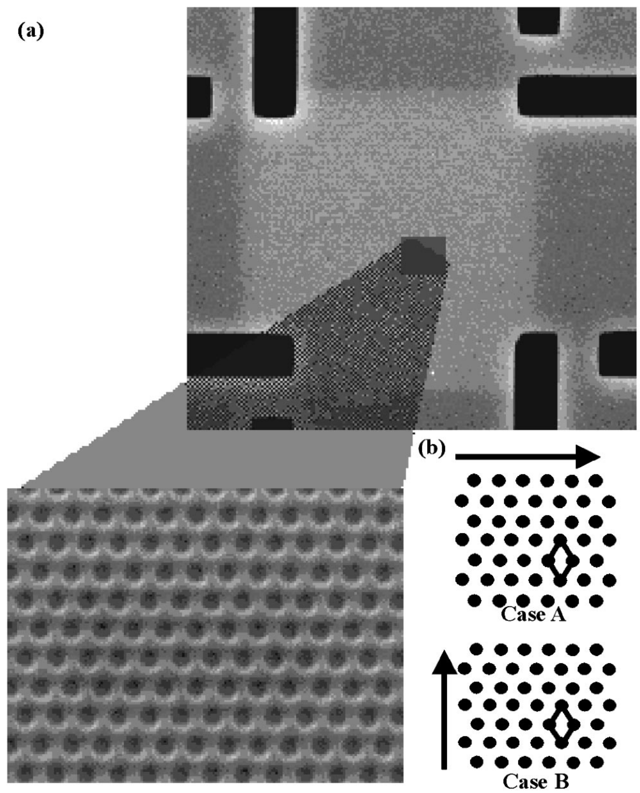

FIG. 1. (a) SEM micrograph of the patterned sample. The triangular arrays of corrugated holes with the spacing of 545 nm and the hole diameter of around 300 nm, embedded in the 100 nm thick superconducting Nb thin films. (b) Schematic of the current geometry relative to the rhombic unit cell. Case A is for the current along the short diagonal, while case B is along the long diagonal direction.

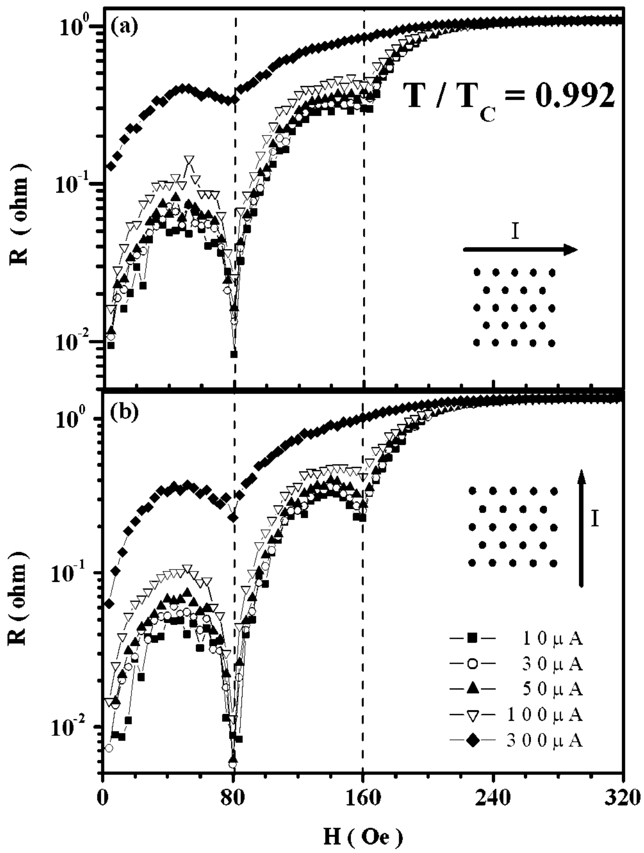

FIG. 2. Magnetoresistance curves, measured at $T=8.49$ K and with different current strengths, obtained in two different current paths for the same Nb device for (a) case A and (b) case B. The nth dip appears at a magnetic field of $B_n=nB_1$, where n is an integer and $B_1=80$ Oe.

ments for this Nb device shows a metallic behavior as a function of temperature from room temperature to the onset of superconductivity, and the superconducting transition is observed to be around $T_{c0}=8.56$ K at zero field.

III. RESULTS AND DISCUSION

As a whole, the MR curves measured in the mixed state rise monotonically as the magnetic field is increased until the normal state, at $T=8.49$ K, as shown in Fig. 2. As the external field is increased, the driving force that was attributed by the transport current or the magnetic field becomes stronger, such that the dissipation caused by the movement of the flux lines is increased. Furthermore, the MR curves with different applied current strengths reveal a set of MR minima at equal external magnetic field intervals for both cases. This can be the ordered array of structure corrugations that clearly induces a pinning effect in the Nb film. As can be seen in Fig. 2, these MR minima appear at equal field intervals of $\Delta B=80$ Oe. This field interval corresponds to a vortex density $n_v=B/\Phi_0=3.9\times 10^8$ cm^{-2}, where Φ_0 is the flux quanta. This is in good agreement with the pinning centers density $n_p=3.89\times 10^8$ cm^{-2} of the triangular arrays of pinning sites. This implies that the defects in the artificial regular arrays that are due to structural corrugation in the Nb thin film act as very strong pinning centers, in contrast to earlier experiments which used magnetic or nonmagnetic dots in the superconductors as pinning centers. Hence, the vortex lattices are highly ordered at nth matching fields and form certain geometrical configurations.

Figure 3 shows the critical current as a function of magnetic field, $I_c(H)$, normalized to $I_{c0}\equiv I_c(H=0)$, at $T/T_c=0.992$. The maxima of critical currents appear at matching fields for both cases. A strong anisotropy is found in the measurements of the critical currents for different current

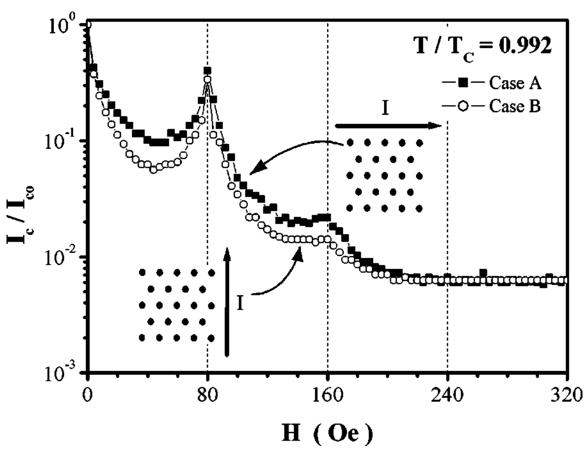

FIG. 3. Critical current as a function of the magnetic field for a Nb film with a triangular array of defects. These curves are for case A (■) and case B (○), respectively.

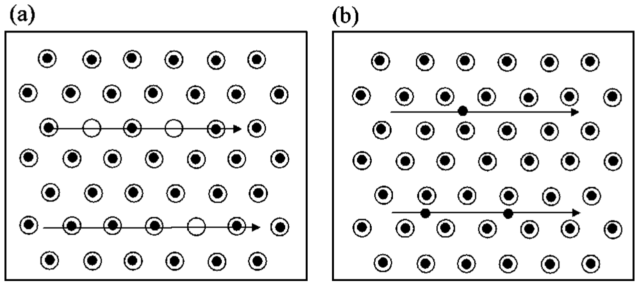

FIG. 4. The vortices distribution (filled circles) and pinning sites (open circles) for (a) the incommensurate row and (b) the interstitial flowing channel.

directions. When the field is equal to the first matching field, both $I_c(H)$ and MR curves do not depend on the direction of the applied current. All vortex-vortex interactions between the vortices pinned in the defects cancel out at the first matching field, so the depinning force of the single-site pinning centers (i.e., the critical current density of superconductors, is the same) as can be seen in Fig. 3. Once the Lorentz force exceeds the pinning forces, all vortices leave their pinning site simultaneously. This experimental result demonstrates that the pinning force of the Nb device is isotropic along both directions. However, when the applied field is departed from the first matching field, the critical current in case A is considerably enhanced to be in case B. The anisotropic pinning properties away from the first matching field are important. This may indicate that the vortices in the patterned film have a great influence, as illustrated in Fig. 4. In this case, the pinning potential created by triangular arrays of the pinning sites forms a clear anisotropic pinning landscape for the vortices. When the applied field is not equal to the first matching field, the vortices can generate an incommensurate row, as shown in Fig. 4(a) and expected by Ref. 2, and the vortex-vortex interaction forces will not cancel out at all. Moreover, in our sample with a triangular array of defects, the vortex-vortex interaction can give rise to the observed anisotropy in the pinning properties, and will result in vortices to easily flow along the short diagonal direction. On the other hand, the pinning potential formed by pinned vortices along the short diagonal can also create a channel to be movable for interstitial vortices, as shown in Fig. 4(b). Thus, it is favorable for these pinned and interstitial vortices to flow along the easier moving channels that were formed along the short diagonal in the unit cell under the action of the Lorentz force.

IV. CONCLUSIONS

We have studied the anisotropic properties in a superconducting Nb film with triangular arrays of corrugated pinning sites. Matching fields are found in the MR and I_c measurements, being in good agreement with the theoretical values based on the geometry of the rhombic unit cells of the pinning sites. A clear anisotropy in the pinning behavior is observed in the vortex dynamics along the two diagonals of the rhombic unit cells of the triangular arrays of pinning sites. The I_c values for the current applied parallel to a short diagonal are higher than that for a long diagonal. When the vortices move along the short diagonal direction, the vortices flow easily and the dissipation energy causing the flux flow is high. The pinning force depends on the direction of the driving force for a sample with the anisotropic geometry of periodic pinning centers. The $I_c(H)$ data support an overall enhancement of the pinning force at all fields for vortices moving along the long diagonal direction. These results indicate that the vortices can be moveable in a straight incommensurate one-dimensional structure.

ACKNOWLEDGMENTS

This work was supported by the National Science Council of the Republic of China under Grant Nos. NSC 91-2112-M-018-012 and 92-EC-17-A-01-S1-026.

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